

Planet signatures in the chemical composition of Sun-like stars

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Abstract

There are two possible mechanisms to imprint planet signatures in the chemical composition of Sun-like stars: i) dust condensation at the early stages of planet formation, causing a depletion of refractory elements in the gas accreted by the star in the late stages of its formation; ii) planet engulfment, enriching the host star in lithium and refractory elements. We discuss both planet signatures, the influence of galactic chemical evolution, and the importance of binaries composed of stellar twins as laboratories to verify abundance anomalies imprinted by planets.

1 Chemical signatures imprinted by planet formation

Metallicity seems to enhance the formation of giant planets, as first suggested by Gonzalez (1997). Subsequent works showed that indeed metal-rich stars have a higher chance of hosting close-in giant planets (e.g., Fischer & Valenti, 2005; Santos et al., 2004), and that the formation of neptunes and small planets have a much weaker dependence on metallicity (e.g., Wang & Fischer, 2015; Schuler et al., 2015; Buchhave et al., 2014; Ghezzi et al., 2010; Sousa et al., 2008).

Besides the effect that the global metallicity of the natal cloud can have on forming different type of planets, dust condensation, the first stage in the formation of rocky planets and the rocky cores of giant planets, will sequester refractory material, causing a non-negligible impact on the composition of the late gas accreted onto the star. This can alter the chemical composition of the convection zone of Sun-like stars, because the gas that is accreted by the star at the late stages of its formation would be depleted in refractory elements, making the star slightly deficient in these elements at the level of just a few 0.01 dex (Chambers, 2010).

Remarkably, a comparison of the chemical composition of the Sun to solar twins by Meléndez et al. (2009), showed that the Sun is deficient in refractory elements (Fig. 1), an observational finding supported by further works (Ramírez et al., 2009, 2010; González Hernández et al., 2010; González et al., 2010, 2010; Schuler et al., 2011a; Nissen, 2015, 2016). This fascinating signature of planet formation, revealed as a strong correlation with condensation temperature (T_{cond}) (Fig. 1), was only unveiled using unprecedentedly precise chemical abundances (0.01 dex), obtained through a strictly line-by-line differential technique of very similar stars observed with the same instrument and setup, thus cancelling out many uncertainties (e.g., transition probabilities, models atmospheres) and systematic effects that plague abundance analyses (Hinkel et al., 2016; Blanco-Cuaresma et al., 2016; Asplund, 2005).

A deficiency of refractory elements has been also observed by Liu et al. (2016a) in the rocky-planet host **Kepler-10**. As this star has a slightly sub-solar metallicity and it is from

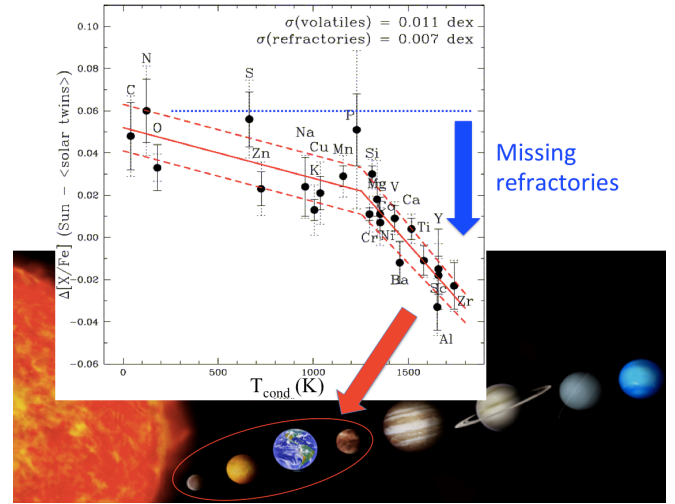


Figure 1: The Sun is slightly depleted in refractory elements (those with high condensation temperatures) when compared to the average abundance pattern of solar twins. The missing refractories were probably sequestered in the rocky planets and rocky cores of giant planets. Notice that the correlation between abundance anomalies and T_{cond} is quite robust, with a probability of 10^{-9} to happen by chance. Figure adapted from Meléndez et al. (2009).

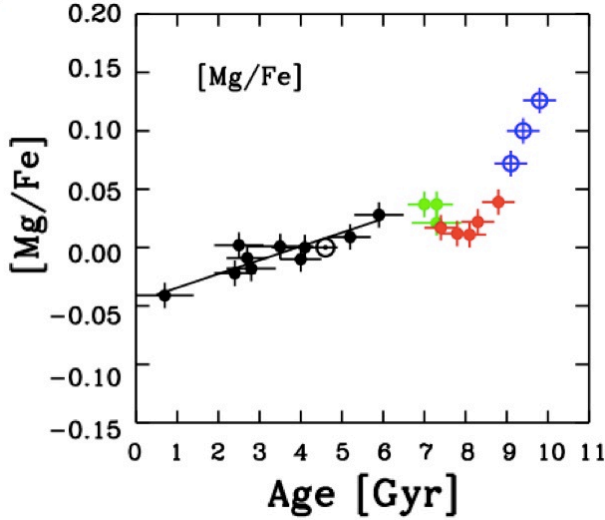


Figure 2: $[Mg/Fe]$ vs. age using solar twins. The three blue circles with the highest $[Mg/Fe]$ abundances are old stars likely from the thick disk. Figure adapted from Nissen (2016).

the thick disk population, the differential analysis was performed using thick disk stars with stellar parameters similar to Kepler-10. The abundance pattern of the Galactic thick disk is distinct to the thin disk, therefore is mandatory to use reference stars from the same population when looking for the chemical signatures of planets.

One issue regarding the imprint of planet formation signatures in the Sun is that its convective zone may have been too massive during the lifetime of the disk, diluting the signal to levels that would be very hard to observe. According to classical stellar evolution models (e.g., D’Antona & Mazzitelli, 1994), it would take about 30 Myr for the Sun’s convection zone to shrink to about its present-day mass ($\sim 0.02 M_{\odot}$), however the lifetime of proto-planetary disks is below 10 Myr (e.g., Mamajek, 2009; Sicilia-Aguilar et al., 2009), albeit there seems to be some dependence with stellar mass, with longer living disks for stars with $M < 2 M_{\odot}$ (Ribas et al., 2015). Note also that Pfalzner et al. (2014) have suggested that the observations that have been used to infer fast disk dispersal may be subject to severe selection effects. A solution to this timescale problem could be the effect of episodic accretion on the stellar structure (Baraffe & Chabrier, 2010). The impact of non steady accretion rates would be significantly higher central temperatures, hence the radiative core develops earlier than in classical models, so that the star can reach a low-mass convective envelope in only about 5 Myr, rather than the 30 Myr needed in classical models.

2 Galactic chemical evolution effects

Adibekyan et al. (2014) suggested that there are no signatures of planet formation in the abundance trends of solar analogs, but instead that the slope with condensation temperature is due mainly to different stellar ages, a $4\text{-}\sigma$ result. They also tested a correlation with galactocentric distances, but found no significant correlation (at about $1.5\text{-}\sigma$). Nissen (2015) also tested a correlation between the slope in T_{cond} and age using solar twins, and found a $2.9\text{-}\sigma$ correlation. In

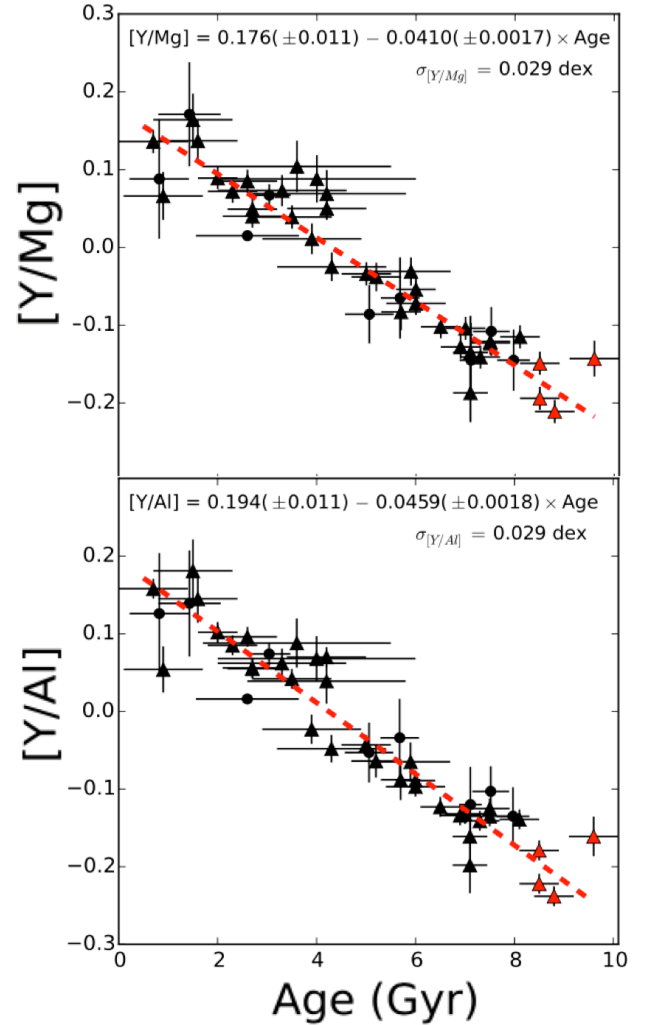


Figure 3: $[Y/Mg]$ and $[Y/Al]$ ratios vs. age based on solar twins. The strong dependence of these abundance ratios with age arise due to the opposite effects of increasing $[Y/Fe]$ for younger stars (due to the increasing contribution by AGB stars) but decreasing $[Mg/Fe]$ and $[Al/Fe]$ ratios. The red triangles represent old stars likely from the thick disk population. Figure adapted from Spina et al. (2016b).

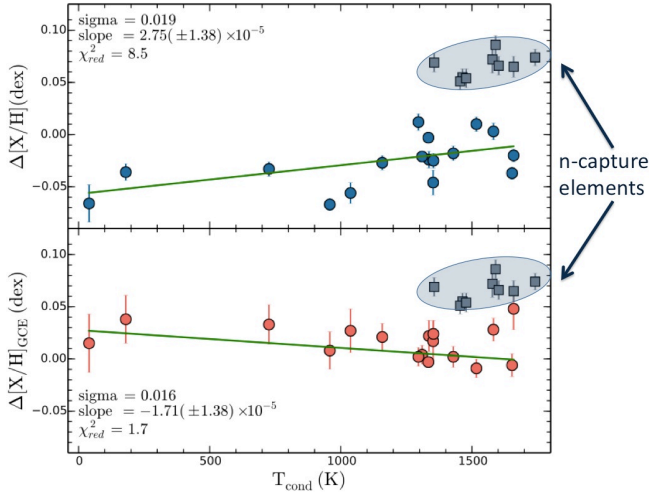


Figure 4: $[X/H]$ ratios vs. T_{cond} in the solar twin HIP 100963. In the upper panel the abundance ratios without GCE correction; notice the high reduced χ^2 (8.5). In the lower panel the abundance ratios after GCE corrections to the Sun's age, with the scatter about the fit now compatible with the abundance errors (including now uncertainties in the GCE corrections) and a much lower reduced χ^2 (1.7). Figure adapted from Yana Galarza et al. (2016).

their latest study using late-F and early G dwarfs, Adibekyan et al. (2016b) confirmed no correlation with galactocentric distance (at the $1.6\text{-}\sigma$ level) and, unlike their previous $4\text{-}\sigma$ result using a smaller sample, now they found no correlation between T_{cond} -slope and age.

Albeit age is not the main driver of trends with condensation temperature, it introduces some variation in the T_{cond} -slope due to the scatter introduced by galactic chemical evolution (GCE). The variation of individual $[X/Fe]$ ratios with age (e.g., Fig. 2) for elements with $Z \leq 30$, was first observed by da Silva et al. (2012) using solar type stars and more clearly shown by Nissen (2015) using solar twins. In follow-up works, Spina et al. (2016a,b) found also correlations between abundance ratios and stellar age. Interestingly, some abundance ratios that include s-process elements such as yttrium ($[Y/Mg]$ and $[Y/Al]$), have a strong dependence with age (Fig. 3), so that they may be useful for age determination (da Silva et al., 2012; Nissen, 2015, 2016; Spina et al., 2016b; Tucci Maia et al., 2016), at least for near solar composition stars; but the metallicity-dependence of those relations needs to be established (Feltzing et al., 2016).

Spina et al. (2016a) suggested that the GCE effects could be disentangled from the planet signatures by removing the $[X/Fe]$ vs. age trends; after this correction the Sun is one of the most refractory-poor stars for its age. Furthermore, modelling the abundances of solar twins using $[X/Fe]$ -age relations and trends with T_{cond} , reduce the scatter of the abundance ratios (Spina et al., 2016b). Using a similar procedure to correct for GCE, Nissen (2016) found that the Sun has the most negative slope with T_{cond} in his sample of solar twins, meaning that the Sun is the most refractory-poor star even after GCE is taken into account. Thus, the deficiency of refractory elements in the Sun is not entirely caused by GCE but it could be related to planets.

When comparing Galactic thin disk stars with ages differing from the Sun, it is important to perform GCE corrections. Yana Galarza et al. (2016) showed that the young (2 Gyr) solar twin **HIP 100963** seems somewhat enhanced in refractories but with a high scatter (0.019 dex) around the fit of $[X/H]$ vs. T_{cond} , more than twice the typical error bar (0.008 dex) in the $[X/H]$ abundance ratios (Fig. 4, upper panel). After correcting the abundance ratios for GCE to the solar age, the abundance pattern of HIP 100963 seems actually solar or slightly depleted in refractories (relative to the Sun). Also, the scatter around the fit is reduced (0.016 dex) and is now compatible with the average error (0.015 dex) that includes the uncertainties in the GCE corrections (Fig. 4, lower panel).

3 Binaries as laboratories to study planet signatures

The study of binaries is key to verify if there are chemical signatures associated with planets. As both binary components arose from the same natal cloud, it is expected that both stars present the same abundance pattern. If the components are twins of each other, meaning very close in stellar parameters (not necessarily solar), precise abundances can be obtained through a careful line-by-line analysis of high resolution spectra, allowing to verify potential abundance differences that could be due to planets (Desidera et al., 2006).

One of the most important binaries to study planet effects is **16 Cyg**, which consists of two solar twins, one of them hosting a giant planet (Cochran et al., 1997). In a fine differential analysis, Laws & Gonzalez (2001) found the stars to differ in metallicity by $\Delta[Fe/H] = +0.025 \pm 0.009$ dex (16 Cyg A - B). A detailed analysis of the system by Ramírez et al. (2011) showed that indeed 16 Cyg A is more metal-rich than 16 Cyg B, not only in iron but also in 23 other elements by about $+0.04$ dex. Nevertheless, Schuler et al. (2011b) found no abundance differences between the components. Notice however that considering the error bars, the results by Schuler et al. (2011b) are consistent with the abundance differences of about 0.04 dex found by Ramírez et al. (2011).

Another study using spectra of much higher quality ($R = 81\,000$, $S/N = 700$) by Tucci Maia et al. (2014), showed abundance differences between 16 Cyg A and B, considerably above their small error bars (Fig. 5), suggesting thus that there are genuine abundance differences that could be related to planets. The most recent study on 16 Cyg (Mishenina et al., 2016) found also abundance differences between the components.

Other binaries of stellar twins hosting planets or debris disks have been carefully studied for abundance differences. Most of these studies strongly suggest chemical abundance anomalies due to planets: **XO-2N/XO-2S** (Ramírez et al., 2015; Biazzo et al., 2015; Teske et al., 2015, see Fig. 6); **$\zeta^{1,2}$ Ret** (Saffe et al., 2016; Adibekyan et al., 2016a); **WASP 94 A/B** (Teske et al., 2016a); **HD 133131A/B** (Teske et al., 2016b).

Albeit abundance anomalies possibly related to planets have been found in 5 binaries so far, no differences have been found between the two components of the **HAT-P-1** binary (Liu et al., 2014). For the systems **HD80606/HD80607** (Saffe et al., 2015; Mack et al., 2016) and **HD20782/HD20781**

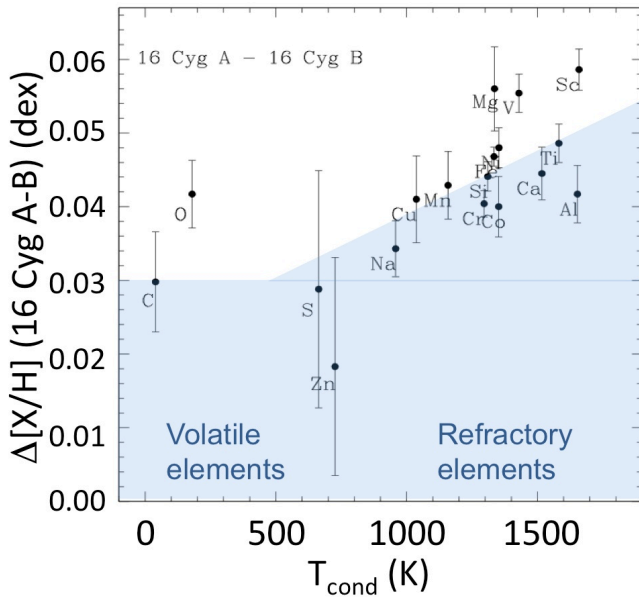


Figure 5: Abundances differences between 16 Cyg A and B vs. condensation temperature, according to the most precise analysis of the system by Tucci Maia et al. (2014). Owing to the extremely high precision, most abundance ratios are several sigma above the 0.0 level, showing thus the existence of genuine abundance differences between the binary components. Interestingly, the refractory elements seem more enhanced than the volatile elements. Figure adapted from Tucci Maia et al. (2014).

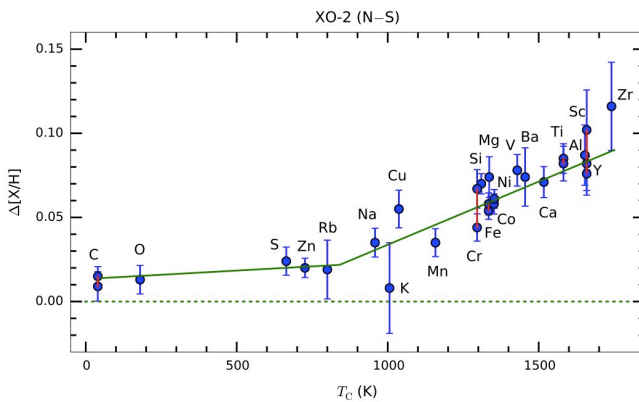


Figure 6: Abundances differences between the planet-hosting stars of the XO-2 binary system. Clear abundance differences are found, especially for the refractory elements. Figure from Ramírez et al. (2015).

(Mack et al., 2014), there are inconclusive results due to relatively high errors in the abundances; notice in particular that in the latter system there is a large temperature difference between the components ($\Delta T_{\text{eff}} = 465$ K, Mack et al., 2014), making it harder to achieve precise abundances.

4 Signatures of planet accretion

Observations of massive neptunes and jupiters in close-in orbits suggest migration from the outer to inner planetary regions. It is possible that planet migration events can induce inner planets to move into unstable orbits and some of them may be engulfed by their host stars, potentially altering their surface chemical composition (Sandquist et al., 2002).

Since Sun-like stars deplete lithium as they age (e.g., Carlos et al., 2016; Andr ssy & Spruit, 2015; Monroe et al., 2013; Denissenkov, 2010; Baumann et al., 2010; do Nascimento et al., 2009), it is easy to increase their Li abundance by planet accretion. Albeit most solar twins analysed by Carlos et al. (2016) follow a well-defined Li-age correlation, they noticed three stars with enhanced Li abundances, among them 16 Cyg A. Interestingly, this star is also enhanced in volatiles and in refractories (Fig. 5). This suggests that the old solar twin 16 Cyg A may not have a planet because it has already accreted it. Note, however, that Deal et al. (2015) argue that if the effects of fingering convection are taken into consideration, surface pollution by metals from an engulfed planet would be quickly diluted, while lithium would in fact be destroyed by mixing processes, in direct contradiction with the statement made above.

Although many planetary systems show evidences of migration of outer giant planets to the innermost regions of their systems, our solar system has a well-defined architecture with small rocky planets in the inner region and giant planets in the outer region. This contrasting configuration may be due to the dynamical barrier imposed by Jupiter, preventing other giant planets (or large rocky cores or giant planets) from ending up in the inner solar system region (Izidoro et al., 2015). If so, then the solar twin **HIP 11915** may be an excellent candidate for a solar system twin, as this star hosts a Jupiter twin (a Jupiter-mass planet in a Jupiter-like orbit) but no other giant planets are detected in the inner region (Bedell et al., 2015). On the other hand, the solar twin **HIP 68468** does not show evidence of a Jupiter analog but it has an inner (0.7 AU) super-Neptune and potentially a hot super-Earth (Mel ndez et al., 2016). The lack of a Jupiter analog perhaps allowed the super-Neptune to migrate inwards where it is observed today. Due to this migration, inner planets may have ended up engulfed by its host star, as suggested by the enhancement of refractory elements and lithium (Fig. 7) detected in this star (Mel ndez et al., 2016).

Another signature of planet accretion is presented by a young star in the **Gamma Velorum** open cluster, as revealed by a large enhancement in the refractory elements, relative to other cluster members (Spina et al., 2015). The effects of planet ingestion on this star are discussed in detail by Tognelli et al. (2016).

5 Conclusions

It seems well-established that planet formation and evolution can imprint distinct signatures in the chemical composition of their host stars. This is evident in the analysis

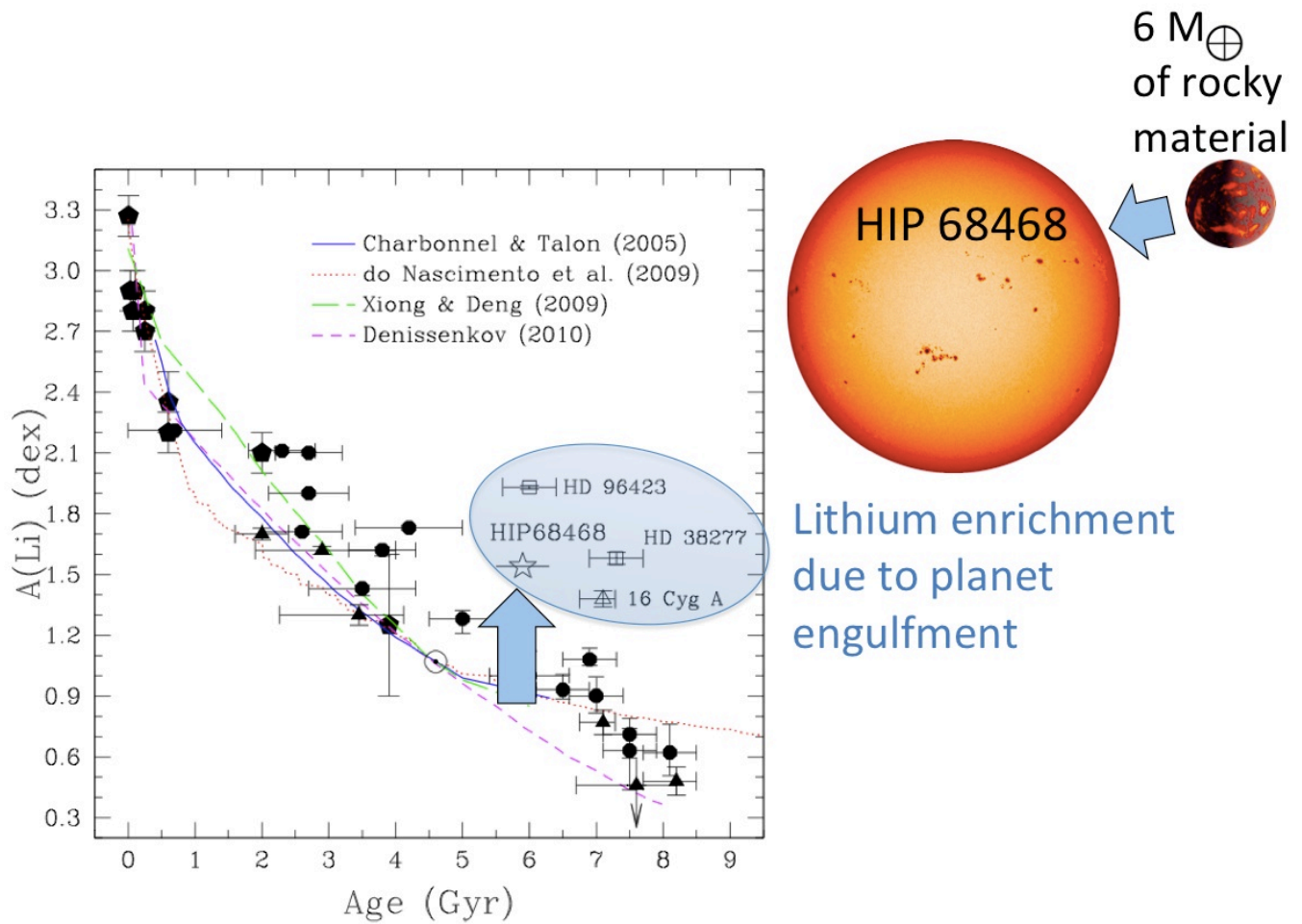


Figure 7: Li-age correlation in solar twins. The enhanced lithium abundance in HIP 68468 may be due to the accretion of 6 Earth masses of rocky material. This amount of planet ingestion can also explain the observed enhancement of refractory elements in this solar twin. Other solar twins shown in the shaded area may have also engulfed planets (Carlos et al., 2016). Figure adapted from Meléndez et al. (2016).

of planet-hosting binaries composed of stellar twins, where high precision can be achieved and abundance anomalies can be related directly to planets.

The abundance ratios are also affected by the chemical evolution of the Galaxy, but as this variation seems predictable, it could be disentangled from the planetary signature. After GCE corrections, the Sun is one of the most refractory-poor stars (Nissen, 2016), strongly suggesting a connection with planet formation.

Besides binaries, open clusters could be used to seek for abundance anomalies due to planets. Unfortunately not much work have been done at high precision yet, except for the clusters Hyades (Liu et al., 2016b) and M67 (Liu et al., 2016c), where small abundance anomalies have been found but they may not be related to planets.

Further studies connecting exoplanet detection/characterization and high-precision chemical abundances in solar twins (e.g., Ramírez et al., 2014; Bedell et al., 2015; Meléndez et al., 2016), binaries (e.g., Ramírez et al., 2015; Teske et al., 2016a,b; Biazzo et al., 2015; Tucci Maia et al., 2014) and open clusters (e.g., Liu et al., 2016c; Brucalassi et al., 2014, 2016; Önehag et al., 2011), can reveal unique information about planet formation and evolution.

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